BRL-TR-3276

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TECHNICAL REPORT BRL-TR-3276

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AN ANALYSIS OF BORE SURFACE TEMPERATURES IN ELECTROTHERMAL-CHEMICAL GUNS

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OCTOBER 1991

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE: October 1991

3. REPORT TYPE AND DATES COVERED: Final, Jan 90 - Dec 90

4. TITLE AND SUBTITLE

An Analysis of Bore Surface Temperatures in Electrothermal-Chemical Guns

5. FUNDING NUMBERS

PR: 1F2Z9W9XDGS3
DA311880

6. AUTHOR(S)

G. P. Wren and W. F. Oberle

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

US Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

BRL-TR-3276

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

Electrothermal-chemical (ETC) guns utilize working fluid/electrical energy combinations which may produce gas temperatures in excess of 3,500 K. The high potential for gas temperatures is of concern due to increased possibility of barrel erosion. However, it is speculated that the fluid propellants form a thermal insulating layer for the gun tube, and, thus, the barrel is protected against excessive erosion. This paper is a theoretical investigation of the reduction of bore surface temperature due to a liquid insulating layer. The analysis considers unsteady heat conduction through a multi-layered hollow cylinder with time-varying convective boundary conditions. The model is used to estimate the thickness of an insulating layer near shot start, based on gas temperature, required to maintain the bore temperature at an acceptable maximum determined from a conventional "hot" propellant. The required mass of fluid in the tube is used to suggest the feasibility of the liquid protecting the bore.

14. SUBJECT TERMS

electrothermal, barrel erosion, heat conductivity, electrothermal-chemical, ETC, electric guns, thermal conductivity

15. NUMBER OF PAGES: 35

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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ACKNOWLEDGMENTS

The authors would like to thank Mr. Irv Stobie and Mr. David Kruczynski for reviewing the manuscript.

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1. INTRODUCTION

In the electrothermal-chemical (ETC) gun, an electrically generated high-pressure, high-temperature plasma interacts with a propellant (working fluid) in the combustion chamber to provide propulsive gases for the projectile. As shown in Figure 1, the armament system consists of a power supply, a pulse forming network and switches, the plasma capillary, the combustion chamber in which the plasma and propellant interact, and the gun tube/projectile. A number of propellants have been proposed for the ETC gun including fluids, gels, slurries, and solids. The temperature of the gas resulting from the plasma/propellant interaction is dependent on the interaction rate between the propellant and plasma as well as material properties of the propellant and plasma. Since the interaction rate remains speculative at present, and the plasma is believed to have a temperature in the range of 10,000 to 20,000 K, it is possible that the gas temperatures may be well in excess of 3,500 K. The high-velocity, high-temperature propellant combustion gases may wash over the bore surface of the gun barrel. Since it is generally accepted that erosion in a gun is a thermally driven phenomena, it might be postulated that erosion in electrothermal guns may exceed that of solid propellant systems (FMC Corporation 1989).

However, proponents of electrothermal technology have hypothesized that, in the case of a liquid propellant, the propellant behaves as a passive thermal barrier. In this scenario, a portion of the fluid initially contained in the combustion chamber is swept into the gun tube behind the accelerating projectile, coating the tube with a layer of fluid as shown in Figure 2 (FMC Corporation 1989; GT-Devices, Inc. 1989). The result may be a thermal barrier similar to that obtained in solid propellant guns through the use of wear-reducing additives.

Prior to 1989, the majority of ETC firings were performed with electrical energy constituting in excess of 50% of the total energy (chemical and electrical). With these electrical energy levels, computed (BLAKE thermodynamic code) effective flame temperatures for the combustion gases were on the order of 3,500 K to 5,000 K. However, weapon system studies indicated that electrical energy inputs of this magnitude would result in unacceptable system mass and volume burdens. Since 1989, the total amount of electrical energy per firing has been reduced to 2–20% of the total energy. At these levels of electrical energy input, effective flame temperatures has been reduced to between 2,500 K to 3,500 K, depending on

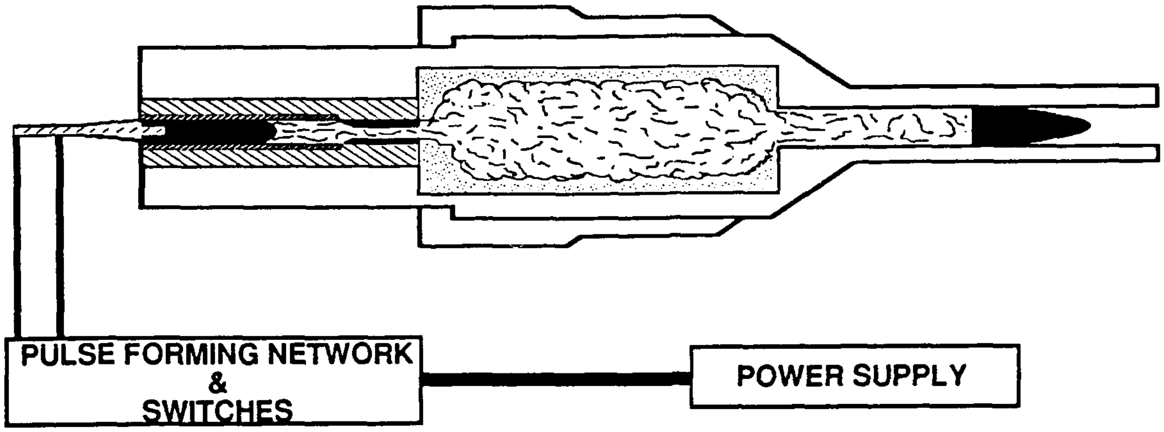

Figure 1. An Electrothermal-Chemical (ETC) Gun.

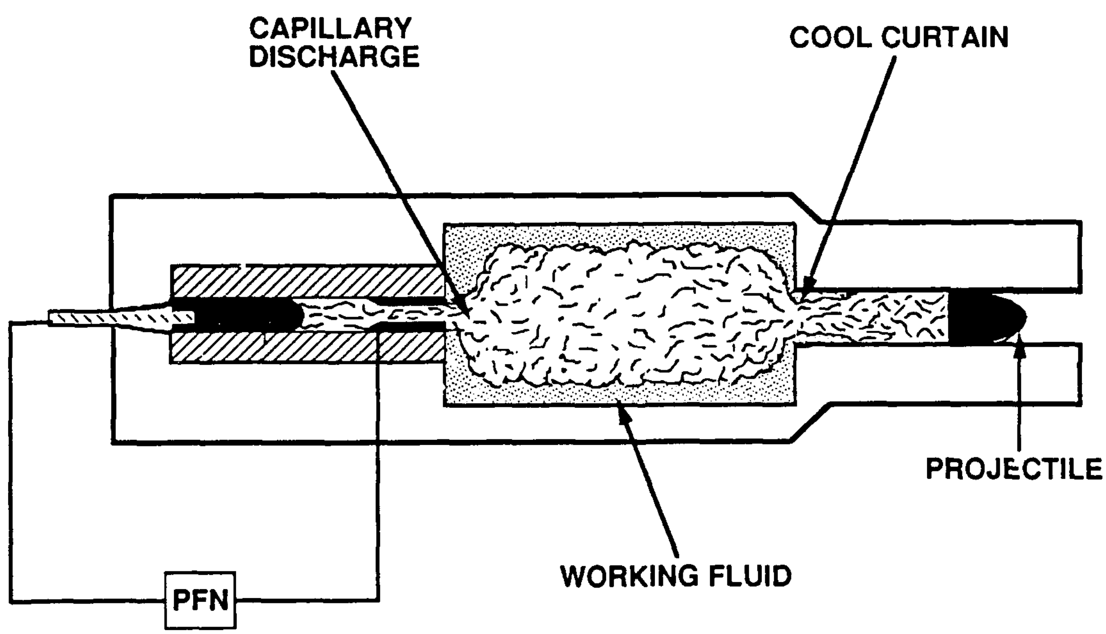

Figure 2. Hypothetical Fluid Insulating Layer in ETC Gun.

the working fluid. However, some studies (Oberle 1989) have suggested that the higher electrical energy levels may be needed to achieve desired performance in missi- . areas such as anti-armor. In addition, the potential exists for gas temperatures higher than normally encountered in guns.

Unfortunately, only limited data currently exist, and much of that data has not been made publicly available, measuring capillary, plasma, gas, chamber and tube wall temperatures. Therefore, the objective of this study is to theoretically determine the effect of a fluid insulating layer on bore surface temperatures assuming a gas temperature regime of 4,000 K.

2. THEORETICAL APPROACH

Two questions are addressed with the following analysis: 1) What decreases in bore surface temperatures can be expected from the presence of a fluid insulating layer? 2) Does it appear feasible to deposit the mass of working fluid required to reduce bore surface temperatures to "acceptable" limits? The first question assumes a relationship between gun tube erosion and barrel temperature which has been empirically validated in a number of studies, although the functional dependence is not known (Stobie, private communication; Kruzysinski, private communication). By way of comparison, a high-performance gun firing with gas temperatures of approximately 3,000 K generally requires a wear-reducing additive to the propellant. A high-performance gun firing JA2, with gas temperatures on the order of 3,400 K, generally requires plating in the tube.

In this study, an acceptable upper bound for bore surface temperature is theoretically established for a 120-mm cannon based on a conventional "hot" propellant, JA2. Prediction of bore surface temperatures for a 120-mm ETC tank gun with a working fluid/electrical energy combination producing gas temperatures near 4,000 K, with and without the consideration of a fluid insulating layer, are then compared to the conventional propellant. The second question regarding the feasibility of producing an insulating layer is addressed by postulating the existence of a fluid layer sufficient in thickness to reduce bore surface temperatures to acceptable levels. The axial distribution of fluid required is then compared with the mass of working fluid initially in the chamber.

The prediction of bore surface temperatures for conventional propellants is obtained from XNOVAKTC (XKTC) (Gough 1980), a quasi one-dimensional, two-phase flow, interior ballistic, hydrodynamic code. XKTC is then used to simulate the gas temperature regime of interest in the ETC comparisons and to estimate the bore surface temperature without an insulating layer.

Utilizing the interior ballistic information, the authors have developed an analysis to compare the effect of a vaporizing, fluid insulating layer on bore surface temperatures. A time-dependent convection coefficient is first derived from the bore surface temperature predicted by XKTC by solving the inverse conduction problem using an alternate pulsating bore surface heat flux boundary condition within an optimization procedure. The derived convection coefficient is then used to obtain a finite-difference solution to the conduction equation assuming the presence of a vaporizing, fluid insulating layer. Although the resulting temperatures cannot be validated for ETC guns due to lack of appropriate experimental data, the method does allow comparisons of bore surface temperatures for ETC guns with conventional guns and, by extension, provide a measure of erosivity.

3. MODEL DESCRIPTION

The barrel heating problem is customarily divided into two main parts: 1) determining the energy transfer from the propellant gases to the gun barrel or, in the case of this problem, to the insulative fluid layer and gun barrel; and 2) determining the radial barrel temperature distribution resulting from this heat transfer. Such a simplification allows the analysis to proceed without a detailed knowledge of local projectile velocity and propellant gas properties and provides a practical approach to an extremely complex problem. The model described here follows this standard approach. However, an estimate of tube heating in the ETC gun necessitates the consideration of a fluid insulating layer whose thickness decreases in response to heating by the hot propellant gases. Thus, the following description of the model is divided into three parts: radial heat flow in the gun barrel wall, determination of the heat transfer coefficient used in the boundary condition, and radial heat flow in the fluid insulating layer.

3.1 Gun Barrel Wall. The model assumes that the gun barrel is a single, circular cylindrical tube and that only radial heat conduction is significant. The governing equation is the Fourier equation of heat conduction in cylindrical coordinates,

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial t}, \tag{1}$$

where α is the thermal diffusivity of the conducting material. By definition,

$$\alpha = \frac{k}{\rho c_p}, \tag{2}$$

where k is the thermal conductivity, ρ is the density, and c_p is the specific heat of the conducting material. A boundary condition of the third kind, also known as Newton's law of cooling, can be written for both the inside and outside surfaces. It is assumed that the predicted gas temperature T_g is nearly the same as the gas temperature actually present at the edge of the thermal boundary layer at the axial location under consideration. The boundary conditions, with heat flow in the outward radial direction defined as positive, are then as follows:

$$\dot{Q}_w = h_i(T_g - T_{bs}) = -k\frac{\partial T}{\partial r},\ at\ r = r_i\ , \tag{3}$$

and

$$\dot{Q}_w = h_0(T_w - T_{amb}) = -k\frac{\partial T}{\partial r},\ at\ r = r_0\ , \tag{4}$$

where r_i is the inside radius, r_o is the outside radius, h_i is the heat transfer coefficient of the inside surface, h_o is the constant heat transfer coefficient of the outside surface, T_g is the gas temperature, T_{bs} is the bore surface temperature, T_w is the outer wall temperature, and T_{amb} is the constant ambient air temperature. The initial condition is as follows:

$$T = T_{amb},\ at\ t = 0\ , \tag{5}$$

where the barrel and initial air temperature are taken to be at 294 K. Thus, the problem is mathematically well-posed.

The barrel is considered to be unplated steel for the purposes of this comparative study, although a layer of chrome plating found in many guns can be considered. The time step Δt is entered, and the stability criteria is applied to choose the grid size Δr such that

$$\Delta r \geq \sqrt{2\alpha_{steel}\Delta t}\,. \tag{6}$$

The heat conduction equation is recast as a finite difference equation, and a predictor-corrector method is used.

3.2 Determination of h_i and T_g. The heat transfer coefficient at the inner surface of the gun barrel is time dependent and is estimated by an approach used by Russell (1975) to determine the effectiveness of wear-reducing additives in solid propellant guns. First an alternate boundary condition developed by Copley and Thomas (1974) is used to represent the pulsating heat flux at the bore surface as an exponential decreasing with time. In the one-dimensional case, the expression for the bore surface heat flux is as follows:

$$\dot{Q} = -k\frac{\partial T}{\partial r} = A_0 \exp(-ct)\ , \tag{7}$$

where A_0 and c are determined from experimental observations. Copely and Thomas show the result of directly adjusting A_0 and c to fit an experimental bore surface temperature-time curve for a single-round firing and demonstrate good comparison with experimental data. Thus, it is assumed, and validated below with experimental data, that an alternate boundary condition at the inner gun surface can be given by Equation 7.

Since experimental gun tube temperature data does not exist at the potential gas temperatures in ETC guns, gas temperature and bore surface temperature without an insulating layer is taken from XKTC. Using the interior ballistic model results, A_0 and c are found by solution to an inverse conduction problem. The values are specified by minimizing the degree of disparity between the predicted surface temperature using the boundary condition, Equation 3, and the bore surface temperature predicted by the interior ballistic model. The multidimensional minimization is the Downhill Simplex Method requiring only function evaluations, not derivatives. The minimization results in a selection of constant values of A_0 and c for a given bore surface temperature profile.

By now combining Equations 3 and 7, the convective heat transfer coefficient relevant to the bore surface can be written as follows:

$$h_i = \frac{A_0 e^{-ct}}{T_g - T_{bs}}\,. \tag{8}$$

The gas temperature T_g and the bore surface temperature T_{bs} are given by the interior ballistic model. Since all values on the right-hand side of Equation 8 are now known, specification of h_i as a function of time can be given.

3.3 Fluid Insulating Layer. When the fluid insulating layer is present, the analysis considers unsteady, radial heat conduction through a two-layer hollow circular cylinder with the time-varying convective boundary condition identified for the bore surface. As the fluid is heated by the combustion gases, it is assumed to vaporize at its critical temperature and to be swept into the gas flow down tube. Thus, the fluid layer decreases in thickness from an initially prescribed value to zero. It is assumed that perfect thermal contact exists between the insulative layer and the gun barrel wall. The assumption that the convection coefficient derived for the uncoated bore surface may be applied to the fluid insulating layer is discussed in detail below.

4. VALIDATION OF ALTERNATE BOUNDARY CONDITION

It is assumed that a function of the form of an exponential decreasing with time,

$$\dot{Q} = A_0 \exp(-ct) \ ,$$

can be selected to represent the pulsating heat flux at the bore surface. The required constants, A_0 and c, are determined from experimental data. A_0 is the value of the heat flux at time zero, and c governs the time rate of decay of the heat flux pulse.

Experimental surface temperature data from a 105-mm gun measured at the bore surface by Veritay Technology, Inc. (Fisher and Chandra, private communication), at shot start, 12 o'clock position is used to verify the assumption. An exponential decreasing with time is chosen to represent the heat flux at the surface as described above. It is then required to minimize the difference between the mathematically predicted bore surface temperature using Equations 1, 3, and 7 and the experimentally measured bore surface temperature. The optimization described above produces values for A_0 of 4,298.8 cal/cm^2-s and for c of 249.7 s^{-1}. The bore surface heat flux is then represented as shown in Figure 3. The bore surface temperature is computed using the optimized values of A_0 and c over the first 10 ms of the firing, since this is the region of interest in determining the maximum bore surface temperature. A comparison of the experimental and computed temperatures is shown in Figure 4. The maximum temperatures are in agreement, although the early temperatures and

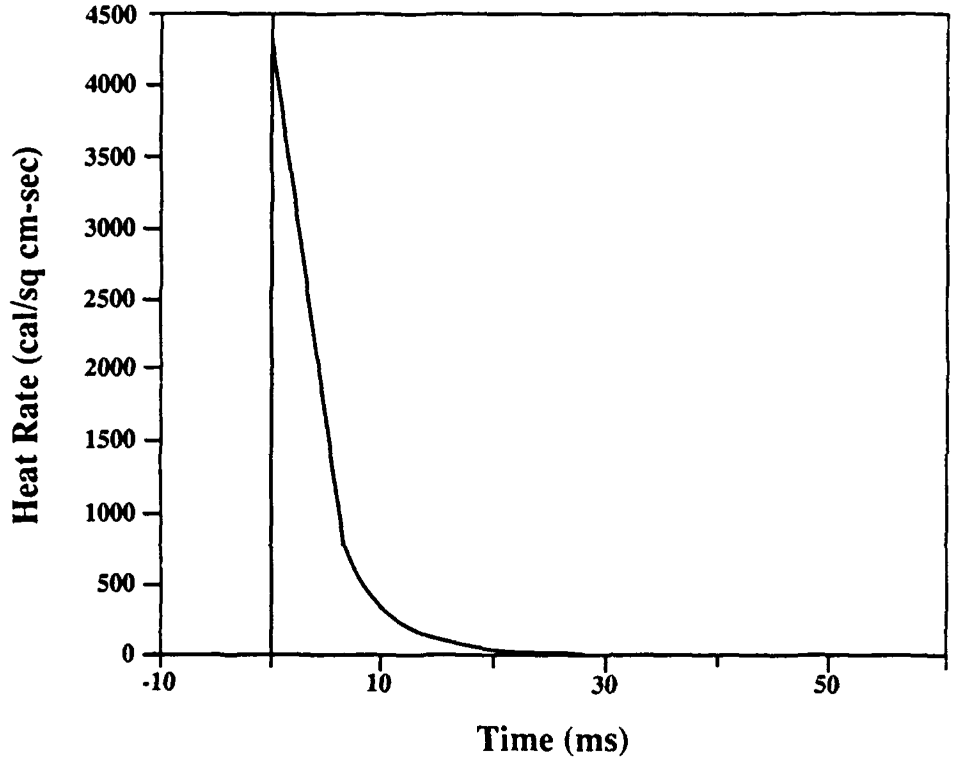

Figure 3. Heat Flux Function Representation.

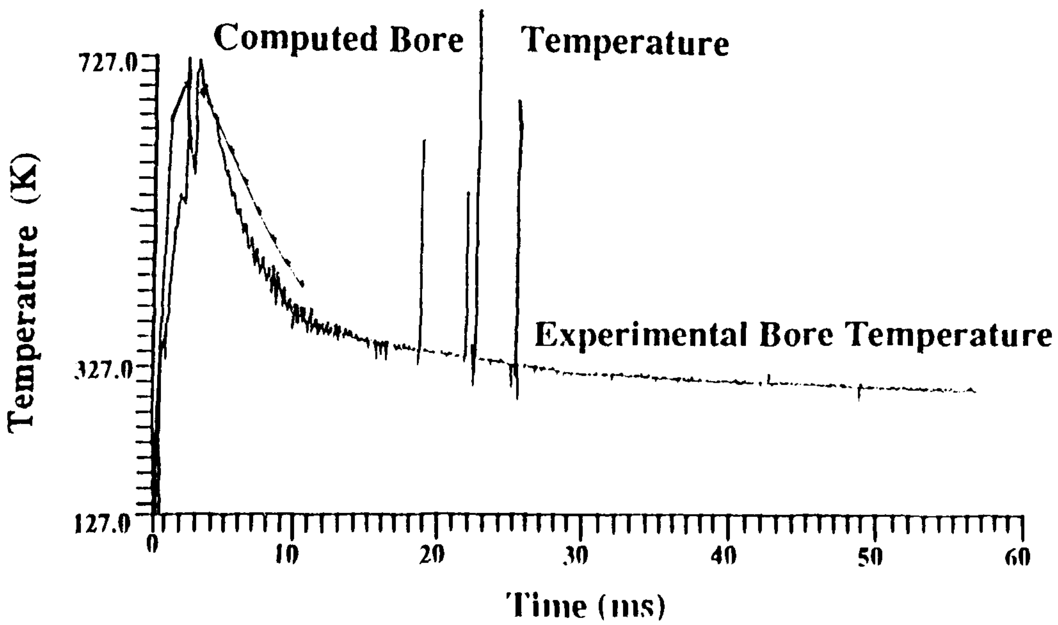

Figure 4. Comparison of Analytical and Experimental Bore Surface Temperature for a 105-mm Barrel.

the temperatures after maximum are overpredicted. However, the characteristic shape of the experimental curve is maintained, and the solution is felt to be in reasonable agreement with the experimental temperature history.

5. APPLICATION TO 120-MM TANK GUN

Although current Army ETC applications are focusing on antiarmor weapons, other mission areas such as air defense are being investigated. Studies have indicated that to achieve the desired performance in these mission areas, it may be necessary to use working fluids which result in gas temperatures near 4,000 K (Oberle 1989). Thus, it is of interest to investigate the impact of a fluid boundary layer on tube heating. Since a large database exists for the 120-mm cannon, this gun will be used in this study. Historically, maximum erosion occurs near shot start. Therefore, this study specifically addresses a location near projectile shot start to determine the necessary thickness of fluid required in an ETC gun to reduce tube temperatures to conventional limits. However, downbore gas temperatures are also of concern. Thus, the analysis is extended to determine the required fluid layer distribution to reduce tube surface temperatures to acceptable levels throughout the barrel.

In order to evaluate the effectiveness of a liquid insulating layer in the gun, it is necessary to characterize the bore surface temperature with no fluid layer present. Since it is not possible to obtain direct experimental bore surface temperature data for a 120-mm tank gun firing a propellant whose flame temperature is 4,000 K, a wall temperature estimate is obtained from XKTC. For comparison purposes, bore surface temperatures predicted by XKTC for the 120-mm gun firing JA2, a conventional propellant with a flame temperature of 3,424 K, are used. The thermochemical properties of JA2 and a working fluid (Freedman, private communication; Bunte and Oberle 1989) with a flame temperature of 3,972 K are shown in Table 1. The working fluid is a 70% hydrogen peroxide and octane mixture with 4 kJ/g of added electrical energy. The mass of propellant is chosen in each case to obtain a maximum breech pressure of 483 MPa. (Robbins, private communication).

The bore surface temperatures predicted by XKTC are utilized in three calculations: 1) the surface temperatures resulting from a 3,993 K flame temperature at 597 mm from the rear face of the tube (RFT) are used to obtain appropriate values of A_0 and c in the

Table 1. Thermochemical Properties of Propellant/Working Fluid Used in Simulations

	Propellant Type	
	JA2	Working Fluid
Mass	8.07 kg	6.55 kg
Impetus	1,143.9 J/g	1,676.2 J/g
Gamma	1.2254	1.1958
Covolume	0.991 cm^3/g	0.808 cm^3/g
Density	1.58 g/cm^3	1.26 g/cm^3
Molecular Weight	24.8226	19.806
Flame Temperature	3,424 K	3,993 K

optimization routine, 2) the surface temperatures resulting from a 3,424 K flame temperature at the same location are used to define the maximum acceptable bore surface temperature, and 3) the surface temperatures resulting from a 3,993 K flame temperature at five locations downbore are used to determine appropriate values of A_0 and c to estimate the thickness of fluid needed to protect the bore during firing.

To produce A_0 and c for the inverse conduction problem, and, in fact, to obtain a solution for the forward problem, thermal properties of the barrel for 4340 steel (Copely and Thomas 1974) are utilized. The values of these parameters as well as values needed in the boundary conditions are shown in Table 2.

Since A_0, c and the bore temperature with no fluid layer are now known, the final information needed to evaluate the inside surface heat transfer coefficient in Equation 8 is T_g, the temperature at the edge of the thermal boundary layer on the bore surface. The gas temperatures are shown in Figure 5 near shot start for the two simulations, JA2 and a working fluid. Although the maximum gas temperatures are somewhat less than the flame temperatures, the temperature difference is approximately the same as the difference in flame temperatures. It is also seen in Figure 5 that the interior ballistic event is completed in a shorter period of time with the more energetic working fluid. Although the maximum breech pressure is 483 MPa in both cases, the muzzle velocity for the electrothermal case is 6.25% higher than the JA2 case (1,785 m/s compared to 1,680 m/s), a motivation for considering

Table 2. Properties of Gun Barrel Used as in Simulations

Thermal conductivity, k	0.088824 cal/cm-s-K
Thermal diffusivity, α	0.100645 cm^2/s
Heat transfer coefficient at outside surface, h_0	0.0005 cal/cm^2-s-K
Initial temperature, T_{init}	294 K
Ambient temperature, T_{amb}	294 K
Outer radius, r_0	12.5 cm
Inner radius, r_i	6.0 cm

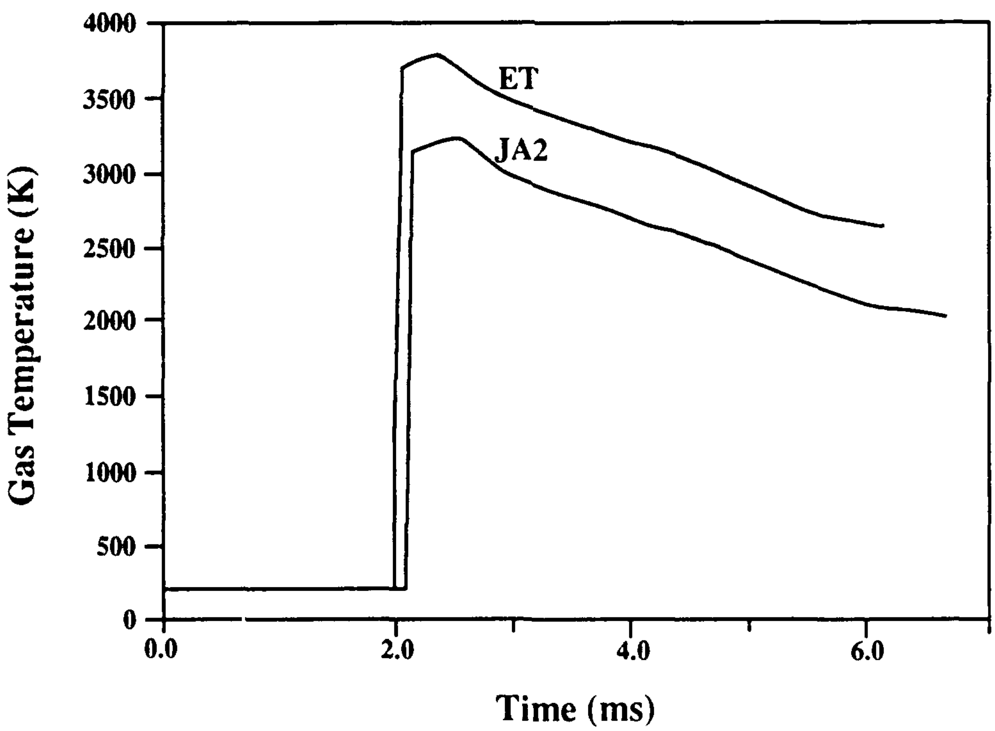

Figure 5. Gas Temperatures Near Shot Start for Propellants with Flame Temperatures of 3,424 K and 3,993 K.

high-flame temperature working fluids. The simulation does not take advantage of the potential for high-loading density and the potential for "flat" pressure-time curve in the ETC calculation. If these two factors were considered, the performance increase would be even greater.

6. EFFECT OF FLUID INSULATING LAYER ON BORE SURFACE TEMPERATURE

The fluid insulating layer consists of a portion of the working fluid originally contained in the chamber. The mechanics of the deposition of the fluid, and the resultant impact on the interior ballistic process, is not addressed. It is assumed for the analysis that a layer of working fluid is in place as the axial position is uncovered by the projectile. The fluid then heats by conduction, and subsequently vaporizes as it reaches its critical temperature. However, two questions are pertinent: 1) Can the thermal properties of the working fluid be characterized? 2) What is an appropriate boundary condition at the surface of the fluid?

To address the first question, it is known that the thermal conductivity of liquids is dependent upon other properties, notably temperature and pressure. However, in the case of liquids no adequate theories are currently available to permit reasonable estimates concerning this dependence (Eckert and Drake 1987). Although experimental data relating thermal conductivity to temperature and pressure is available for some liquids, gun conditions quickly exhibit pressures and temperatures beyond the range of current experiment.

Thus, it is assumed that the thermal properties of the liquid are constant at the values measured at elevated conditions. However, the nature of the liquid layer itself is determined by the chemistry of the working fluid. Although water will absorb heat and transform to gas at its critical temperature, 647.3 K, mixtures containing hydrogen peroxide or methanol decompose exothermically, that is, with the liberation of heat. Since the current interior ballistic calculation cannot predict gas temperatures accounting for heat and energy addition from a fluid layer in the barrel, the working fluid is assumed to consist primarily of water which forms the fluid insulating layer. Water is also well characterized and does not exhibit large variation in thermal properties (Bridgman 1923). The thermal properties used for water are shown in Table 3 (Reid, Prausnitz, and Poling 1987). Thus, this study provides a lower bound on the required thickness of the insulating layer. If liberation of heat in the tube, convective

Table 3. Thermal Properties of Water Used as Input to Simulation.

Thermal conductivity, k	0.00122 cal/cm-s-K
Thermal diffusivity, α	0.001274 cm^2/s
Initial temperature, T_{init}	294 K

and radiative heating, and the mechanics of fluid deposition are considered the required thickness of the fluid layer would no doubt increase.

The second question leads to a key assumption for the subsequent analysis. It is assumed that the convection coefficient derived for the bore surface does not change when the bore surface is coated with a fluid layer. Several observations support the plausibility of the assumption. The derived convection coefficient is primarily a function of the thermophysical properties of the gas in the boundary layer on the bore surface. Since the gas temperature, velocity, and pressure is assumed to be unchanged when a fluid water layer is present, the gas conditions are the same with or without a fluid layer. In a study of the effectiveness of wear-reducing additives in solid propellant guns, Russell (1975) states that although an insulative coating will affect the temperature distribution in this thermal boundary layer causing some change in the temperature-dependent thermophysical properties, the effect should be minimal, and the convection coefficient may be considered equivalent for both cases.

Also, in the case of a water layer, the fluid vaporizes at its critical temperature of 647.3 K and is swept downbore. Since the gas is much hotter, large changes in the value of the convection coefficient produce equivalent results. For example, changes in h_i of $\pm 10\%$ produce no difference in the solution. Thus, the solution is not unduly sensitive to the value of h_i obtained for the uncoated bore surface. In addition, the fluid layer is quickly depleted, and the condition of the uncoated bore surface is restored.

The effect of fluid layers of varying thicknesses on the bore surface temperature is shown in Figure 6 from the time of exposure of the axial location to hot gas to the time just before projectile exit. The simulation considers a flame temperature of 3,993 K which produces the

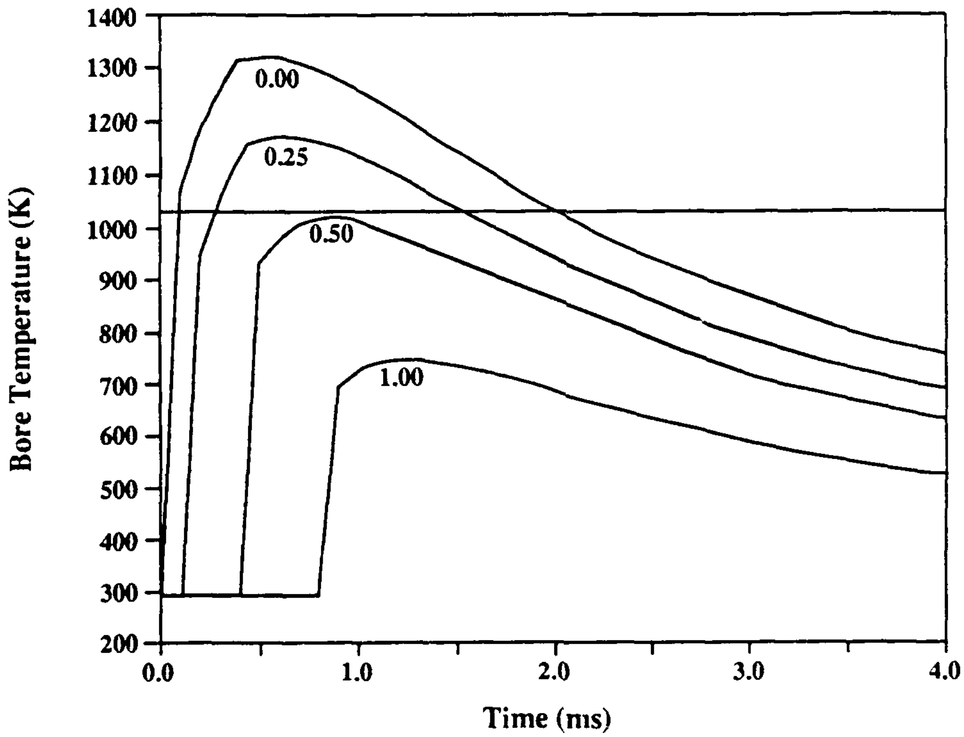

Figure 6. Bore Surface Temperature Near Shot Start With Varying Film Thicknesses of 0.0, 0.25 cm, 0.50 cm, and 1.0 cm.

gas temperature profile shown in Figure 5. The convective boundary condition is used in all cases with the value of h_i obtained as discussed previously. The convection coefficient is derived from the bore surface temperatures produced by XKTC with no fluid layer present, the 0.00 curve in Figure 6 where the zero in time is the initial rise in gas temperature at 2.0 ms in Figure 5. Also shown in Figure 6 are the reduced bore surface temperatures obtained with a vaporizing fluid layer initially 0.25, 0.50, and 1.0 cm thick. As expected, as the thickness of the fluid layer increases, the bore surface temperatures decrease. Thicker fluid layers are more effective in reducing the bore surface temperature since the bore is protected during the elevated gas temperature regime in the initial portion of the interior ballistic cycle.

As a reference line in Figure 6, the maximum bore surface temperature obtained from XKTC using the baseline JA2 case is indicated by the horizontal line at 1,029 K. Since maximum bore surface temperature is implicated as a factor in tube erosion, and JA2 is

considered an upper limit temperature propellant, this line indicates an upper limit on acceptable temperature. Therefore, the results suggest that a fluid layer of water initially 0.50 cm thick is necessary to insulate the bore near shot start and maintain tube temperature within conventional limits. Thicker fluid layers can substantially reduce bore surface temperatures.

7. EFFECT OF AXIAL DISTRIBUTION OF FLUID INSULATING LAYER

Although the previous analysis addresses the thickness of the fluid layer necessary to reduce the bore surface temperature to a conventional maximum, the feasibility of depositing the required mass of fluid is not considered. However, one measure of determining the likelihood of coating the tube with sufficient liquid to reduce bore surface temperatures to 1,029 K, the hypothetical upper bound, is to consider an axial distribution of fluid. It is possible to determine the thickness of fluid needed at axial locations downbore and to obtain a measure of the percent of working fluid mass in the tube. The higher the required percentage of mass, the less the feasibility of depositing the fluid.

Therefore, the analysis is applied to the locations shown in Figure 7, namely, at 55.8, 59.7, 72.4, 85.1, 97.8, and 110.5 cm from the RFT. The bore surface temperature is restricted to a maximum of 1,029 K. The required thickness of fluid is then determined as illustrated in Figure 7. At 111.8 no fluid layer is required, and the calculation terminates at 110.5 cm.

Under each axial position (Figure 7, in parenthesis) is the required thickness of fluid to reduce bore surface temperature to 1,029 K. Computing the mass of fluid in the tube, and comparing the result to the initial mass of working fluid, it is found that 13.5% of the working fluid is required in the bore. It is necessary for the fluid to extend for 4.55 calibers, or 11.5% of the projectile travel. These values suggest that a fluid insulating layer of sufficient thickness to protect the bore may be difficult to obtain in electrothermal guns. Also, the pertinent interior ballistic implications of moving this quantity of fluid and releasing energy in the tube should be addressed.

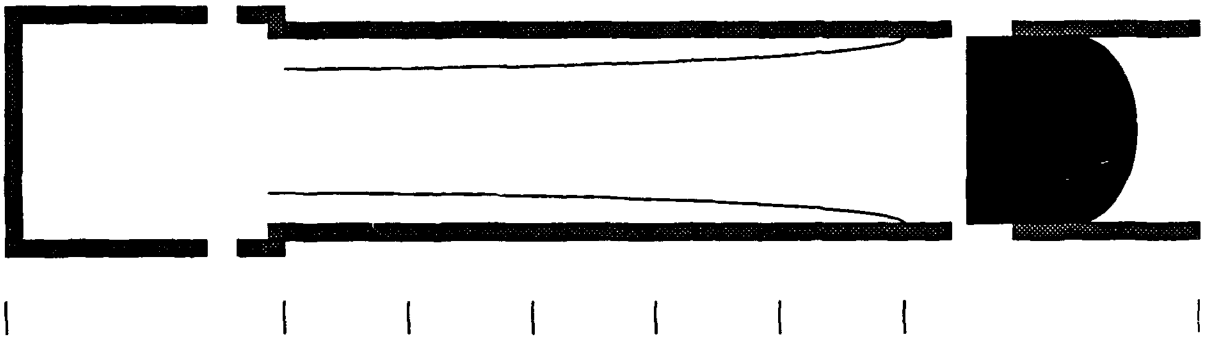

Figure 7. Diagram of 120-mm Gun Showing Required Thickness of Fluid Needed to Reduce Bore Surface Temperature to 1,029 K.

8. TOTAL HEAT INPUT

Besides maximum bore surface temperature, total heat transfer per unit area to the gun surface is sometimes given as a measure of erosion. Total heat input can be determined from the boundary condition assuming a decreasing exponential with time. Since

$$\dot{Q} = -k\frac{\partial T}{\partial r} = A_0 \exp(-ct) , \tag{9}$$

then

$$Q = \int_0^\infty -k\frac{\partial T}{\partial r}dt = \int_0^\infty A_0 e^{(-ct)}dt = \frac{A_0}{c} . \tag{10}$$

Using the values for A_0 and c obtained from the optimization procedure, one obtains an estimate of total heat input near shot start, as shown in Table 4.

Table 4. Theoretical Total Heat Transfer Per Unit Area Near Shot Start

Configuration	Total Heat Transfer Per Unit Area Near Shot Start
Baseline JA2	9.69 cal/cm^2
ETC Gas Temperature 3,993 K without fluid insulating layer	12.61 cal/cm^2
ETC Gas Temperature 3,993 K with 0.5 cm insulating layer	8.5 cal/cm^2

Thus, the presence of the fluid insulating layer of sufficient thickness substantially reduces the total heat input per unit area to the bore surface near shot start compared to the case of no fluid layer. Since the total heat input with a fluid insulating layer is lower than the baseline JA2 case and maximum bore surface temperature is equivalent, it appears that tube erosion should be no worse given sufficient fluid in the tube.

9. CONCLUSIONS

A model has been developed to estimate the reduction in bore surface temperature expected with a fluid insulating layer. Although the derived bore surface temperatures cannot be treated as a quantitative prediction due to the many assumptions used in the analysis, a comparison with a baseline solid propellant provides a measure of the amount of fluid required to reduce temperatures to conventional limits. A measure of the total heat input per unit area to the bore near shot start can also be obtained. However, the analysis is dependent upon accurate values of the uncoated bore surface temperature to empirically determine values for the heat transfer coefficient and requires accurate gas temperatures. The model is limited by this assumption since accurate experimental measurements are not available for ETC guns. In addition, the values obtained for fluid thickness are most likely underestimated since in-bore combustion of the fluid has not been considered.

The analysis shows that for the case of a 3,993 K flame temperature propellant with a water insulating layer in the 120-mm cannon: 1) a fluid insulating layer of sufficient thickness of water can substantially reduce bore surface temperatures; 2) it is possible to reduce bore

surface temperature sufficiently given approximately 15% of the initial fluid to insulate the tube; and 3) the total heat input per unit area to the tube can be reduced to conventional values assuming the presence of a fluid insulating layer. By extension, relating tube erosion to maximum bore temperature and total heat input, erosion may be minimized in ETC guns by the presence of a fluid insulating layer even at high gas temperatures.

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